

Focusing Solenoids

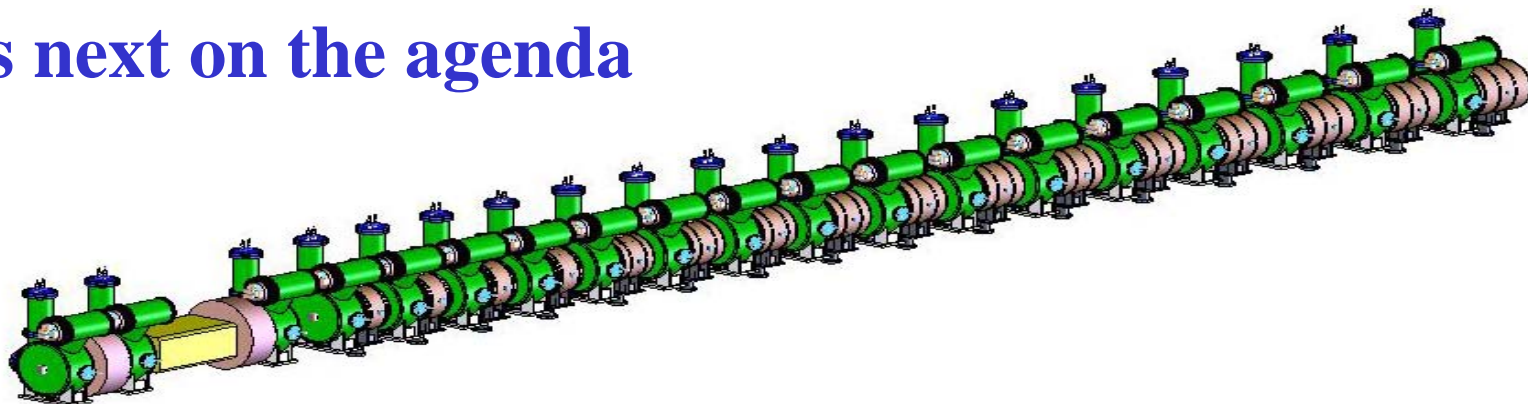
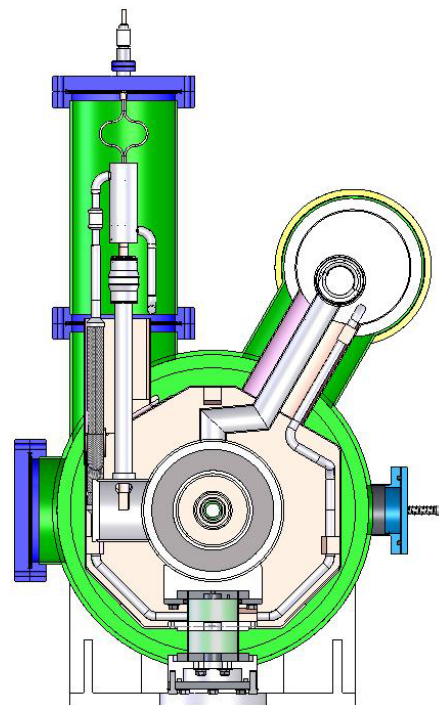
Yuri Tereshkin

Fermilab Accelerator Advisory Committee

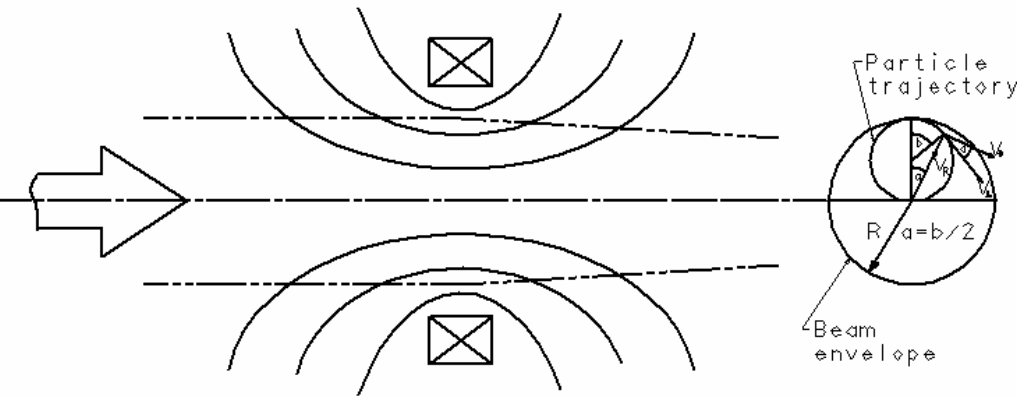
May 10th – 12th , 2006

Outline

- Introduction to Solenoid Focusing
- Requirements and Availability
- R&D Issues:
 - Magnetic Modeling
 - Strand Choice
 - Stress Management
 - Quench Protection
- Test Coil Program
- What's next on the agenda



How It Works



1. Radial component of a fringe field combined with asymmetric particle rotation provides radial component of the particle velocity;
2. Rotation in the longitudinal field results in different azimuthal position of the particles after the lens.

Focusing length:

$$f = R \cdot \frac{\beta c}{v_R} = 4 \frac{m^2}{q^2} \beta^2 c^2 \cdot \frac{1}{B_c^2 L_{eff}} = \frac{8 \cdot \frac{m}{q} \cdot T(eV)}{B_c^2 L_{eff}}$$

Example: $B = 5\text{T}$, $L_{eff} = 7.5\text{ cm}$ ($\sim 3''$) $\rightarrow f = 13\text{ cm}$;

Distance between the lenses must be shorter than 0.5 m;

To increase this distance, L_{eff} and/or B_c must be adjusted \rightarrow beam size increases.

Brillouin field: $\mathbf{BB}^2 = 6.9 \cdot 10^{-7} \cdot \mathbf{I} / (\mathbf{a}^2 \cdot \mathbf{U}^{1/2})$ $\mathbf{a} = 2\text{ mm}$, $\mathbf{U} = 50\text{ kV}$, $\mathbf{I} = 40\text{ mA} \rightarrow \mathbf{BB} = 55\text{ Gs}$

Requirements

	MEBT / RT CH	SSR-1	SSR-2
Number of solenoids in the section	19 (3 + 16)	18 (9 x 2)	6
<u>Parameter</u>			
Bore diameter	20 mm	30 mm	30 mm
Bore type	warm	cold	cold
Field Integral FI = $\int B^2 dl$ (T ² ·cm)	180	300	500
Margin	30%	30%	30%
<u>L_{eff} (cm) @ B_m</u>	< 10 cm		
Field extension	< 2* <u>L_{eff}</u>	Sharp edges	Sharp edges
Cryostat type	Stand alone	Integrated	Integrated
Cold mass length (mm)	130	219	294

- Integrated strength: $FI = \int_{-\infty}^{+\infty} B_z^2 dz$

- Effective length: $L_{eff} = \int_{-\infty}^{+\infty} B_z dz / B_0$

- Field integral ratio over $2L_{eff}$: $FIR = \int_{-L_{eff}}^{+L_{eff}} B_z dz / \int_{-\infty}^{+\infty} B_z dz$



Examples of Implementation

Linac:	RIA-MSU	Amer. Magnetics	Cryomagnetics	ISAC-II, TRIUMF	SARAF
Parameter					SOREQ, Israel
Bore diameter	40 mm	30 mm	52 mm	26 mm	35 mm
Bore type	Cold	Cold	Warm	Cold	Cold
B2L (m*T^2)		12.55 T2m		~27.5, ~36.4 @ 9T	
Bm	9 T	9 T	17 T	9 T	6 T
Leff	100 mm			400 mm, 500 mm	88 mm
Lmax	340 mm	300	385 mm	550 mm, 680 mm	280 mm
Transverse Dimension	300 mm		280 mm	OD 325 mm; 370 mm	
Fringe Field Compensation	End bucking coils. Nb Shield (150 Gs)	End bucking coils. Iron Shield	Non	End bucking coils	Active Shield
Fringe Field Level @ cavity wall	10 mGs	300 Gs		~ 800 Gs @ 130 mm from the end	~ 200 Gs @ cav
Magnetic field at "zero" current				10 Gs	100 mGs (10 mkT)
Temperature	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K
Material	Nb-Ti-Ta	Nb-Ti	Nb-Sn?	Nb-Ti	Nb-Ti, 0.6 mm
Current	68 A (98 max)			95 A @ 9T; 107 A @ 11 T	
Manufacturer	Cryomagnetics	Am. Magnetics	Cryomagnetics	ACCEL	ACCEL
Year		2002		2004	
Source	Terry Grimm	Note	Advert	Bob Laxdal, George Clark	Mike Pekeler
Cost	~ 70 K			100 KE - prototype, ~ 50 K product.	~ 20 K



Solenoid R&D Constituents



Coordination:

J. Tompkins,
I. Terechkin



Strand R&D:

E. Barzi,
D. Turrioni,
T. Wokas,
A. Makarov



Modeling:

V.V. Kashikhin,
B. Wands,
P. Bauer,
I. Terechkin

Design:

G. Davis,
T. Page,
T. Wokas,
I. Terechkin



Fabrication:

TD Procurement,
T. Wokas

Test Preparation:

T. Wokas,
Y. Pischalnikov
and MTF stuff



Testing:

M. Tartaglia,
and MTF stuff



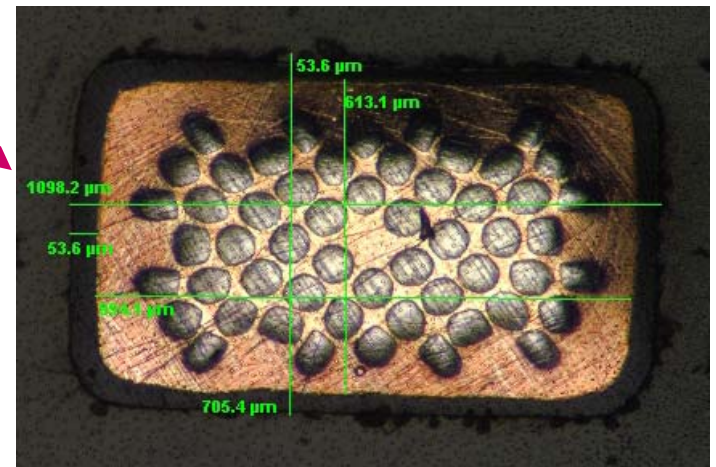
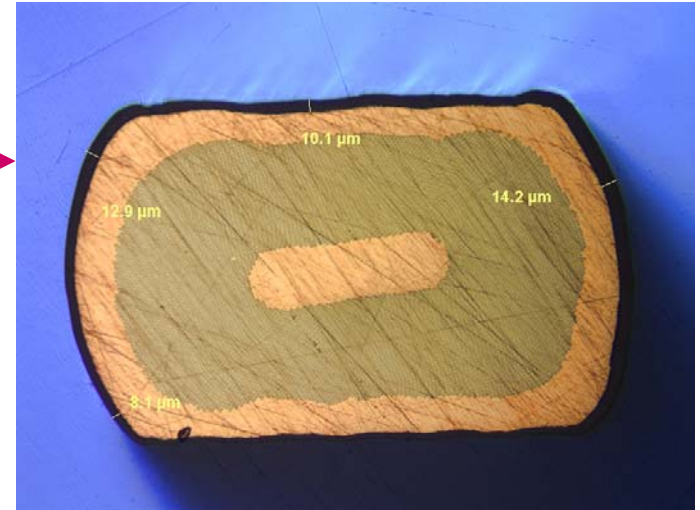
Test Results Analysis:

M. Tartaglia,
I. Terechkin

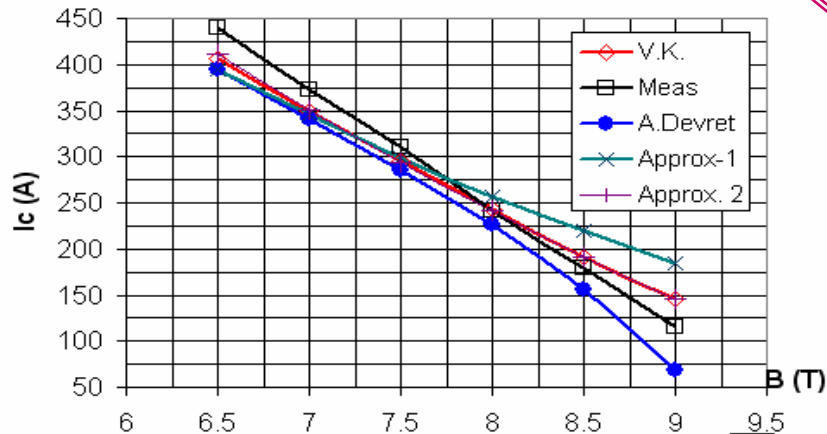


Strand R&D

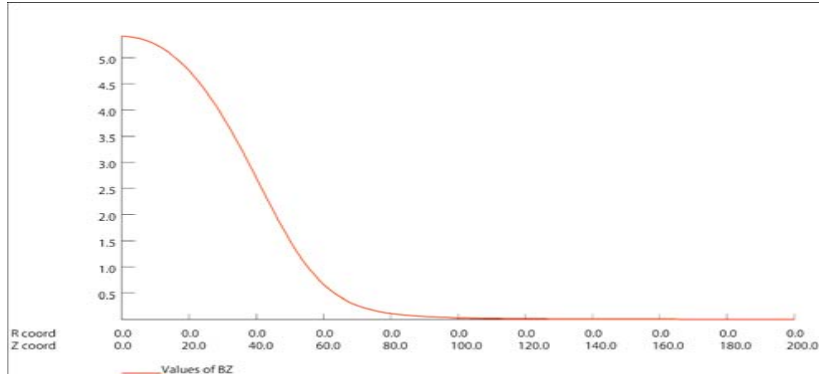
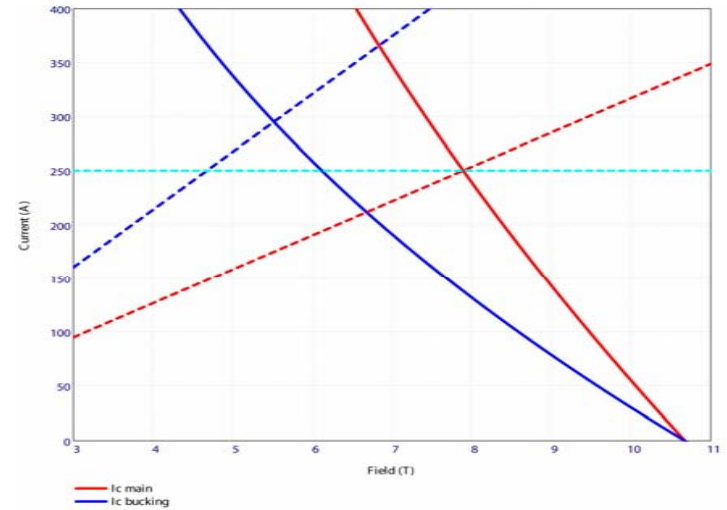
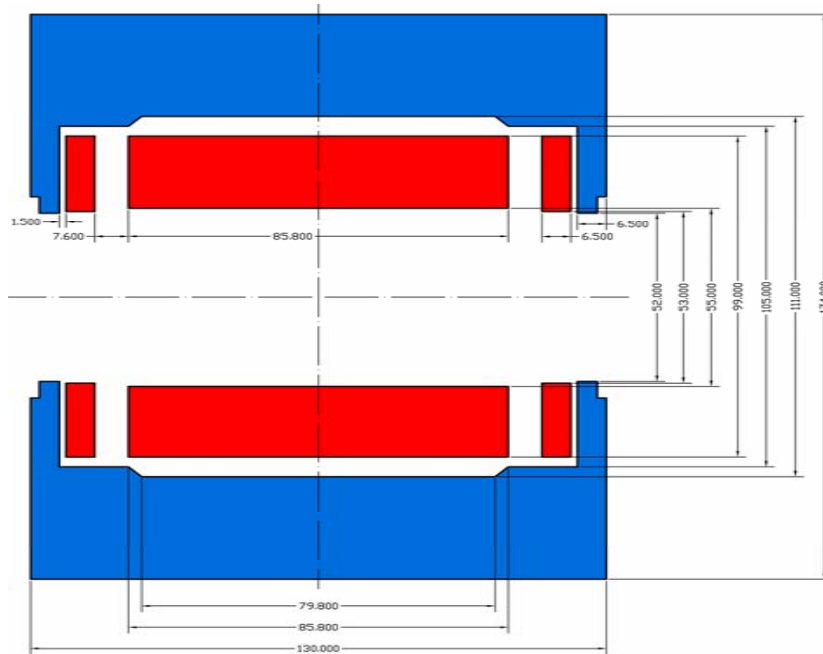
- SSC dipole inner layer NbTi strand (IGC):
strand diameter ~ 0.808 mm
filament diameter ~ 6 mkm \longrightarrow
- Modified SSC strand to increase coil compaction factor
- “Oxford” rectangular 0.9×0.6 mm² strand
filament diameter ~ 70 mkm \longrightarrow
- Round Oxford strands for compensation coils



Strand Critical Surface Comparison Table @ 4.2 K



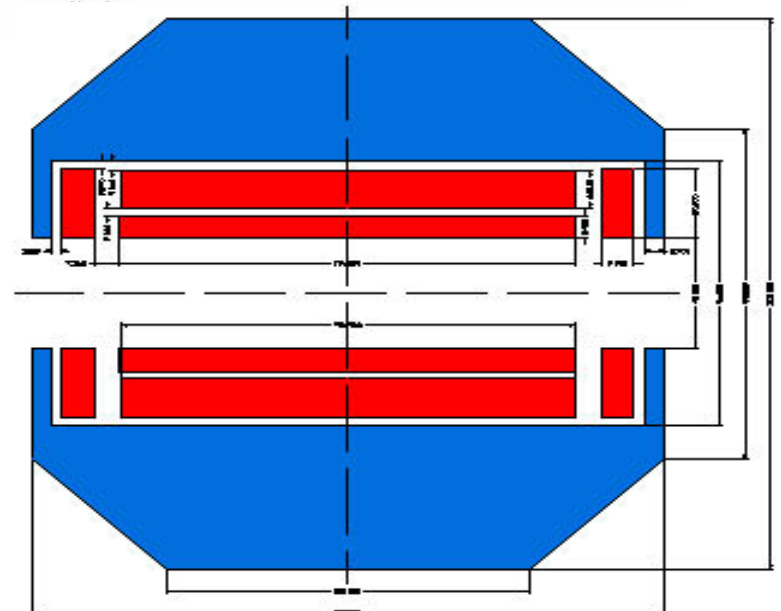
Magnetic Modeling



UNITS
 Length : mm
 Flux density : T
 Field strength : A/m
 Potential : Wb/m
 Conductivity : S/m
 Source density : A/mm²
 Power : W
 Force : N
 Energy : J
 Mass : kg

PROBLEM DATA
 D:\Project\OPERA\2D\
 PD\Solenoid\PDs_RT_
 9 sit
 Quadratic elements
 Axi-symmetry
 Modified Rvec pot.
 Magnetic fields
 Static solution
 Scale factor = 188.04
 14679 elements
 29580 nodes
 10 regions

OPERA-2d
 Pre and Post-Processor



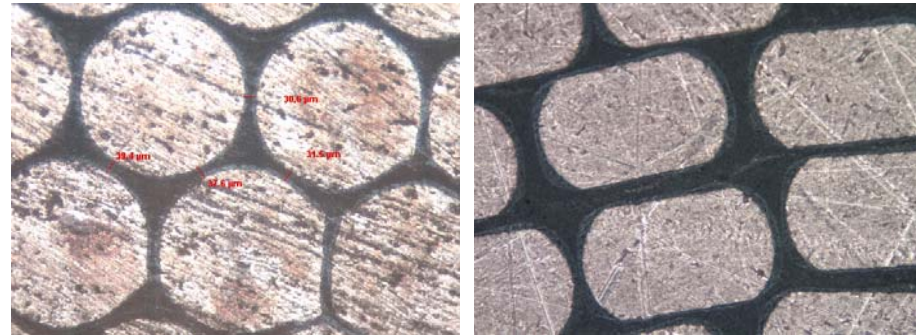
Magnetic Modeling

Strand Parameters

Parameter	Unit	Main	Bucking
Bare (round) strand diameter	mm	0.808	0.600
Strand insulation thickness	mm	0.025	0.025
Copper to non-copper ratio	-	1.3	1.3
Non-Cu critical current density at 5 T, 4.2 K	A/mm ²	2750	2750
Engineering current density at 1 A current	A/mm ²	1.3774	-2.4749

Packing (or compaction) factor:

$$K = \sum(S_{\text{strand}}) / S_{\text{coil}}$$



Global Parameters

Parameter	Unit	Value
Coil aperture	mm	55
Number of turns in the main coil	-	100x26
Number of turns in the bucking coils	-	2x10x37
Average strand packing factor in the main coil	-	0.71
Average strand packing factor in the bucking coils	-	0.70
Yoke length	mm	130

Performance at quench

Magnet current	A	250.32
Central field, B_0	T	7.156
Peak field in the coil, B_{peak}	T	7.894
Field integral, FI	T ² cm	314.65
Effective length, L_{eff}	mm	81.774
Field integral ratio over $2L_{\text{eff}}$, $FIR \cdot 100\%$	%	98.68
Peak radial field at 10 mm off the axis	T	0.87
Stored energy	kJ	7.796
Magnet inductance	H	0.249
Axial force per bucking coil	kN	45.90

Stress Management

- **Stress accumulation during winding**
- **Stress generation during cooling down**
- **Stress redistribution during excitation**
- **Pre-stress application during assembly**

Main Results of study in:

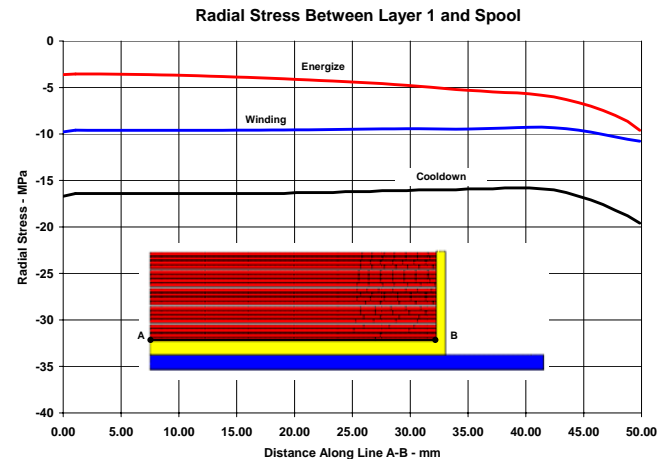
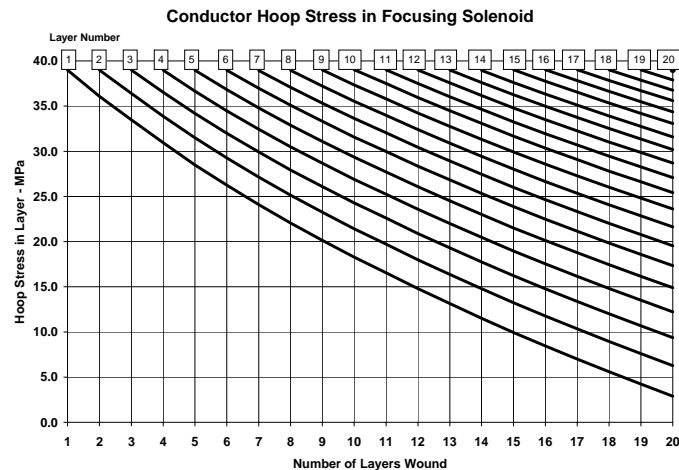
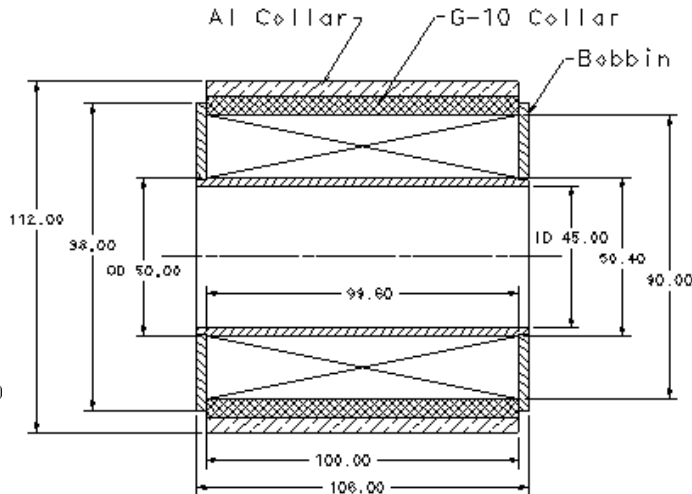
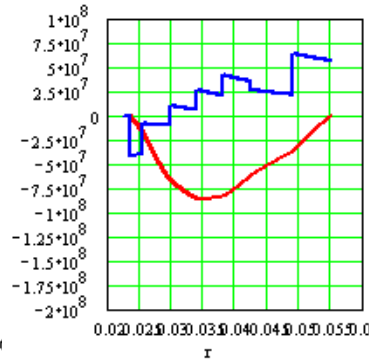
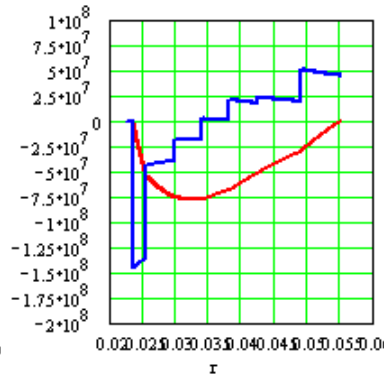
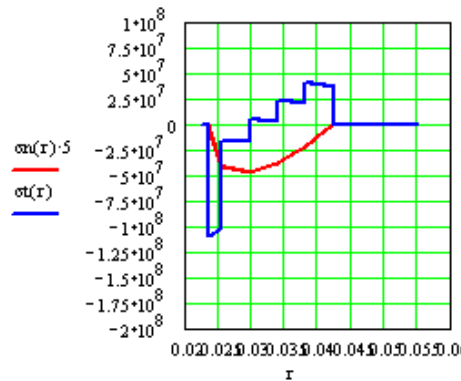
1. Analysis of Stress in PD Front End Solenoids - TD-05-039;
2. Test Solenoid Design Proposal – TD-05-040;
3. Review 08-31-05
4. Bob Wands: TD-06-018, TD-06-19
5. G. Davis, et al, TD-06-020

Stress Management

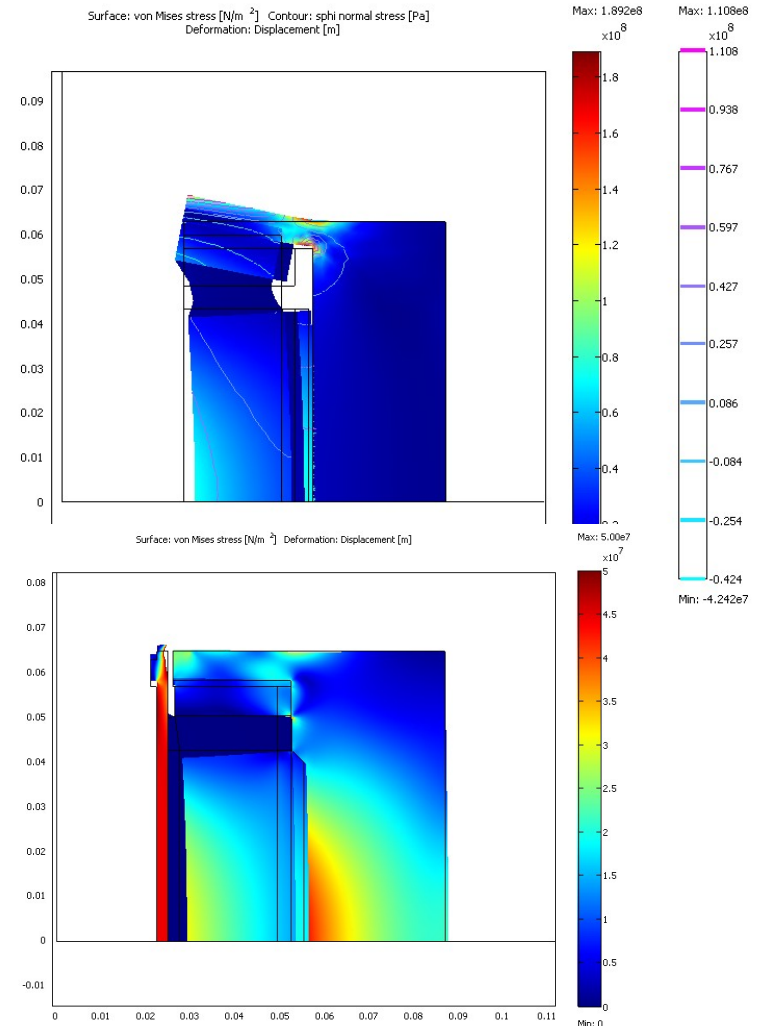
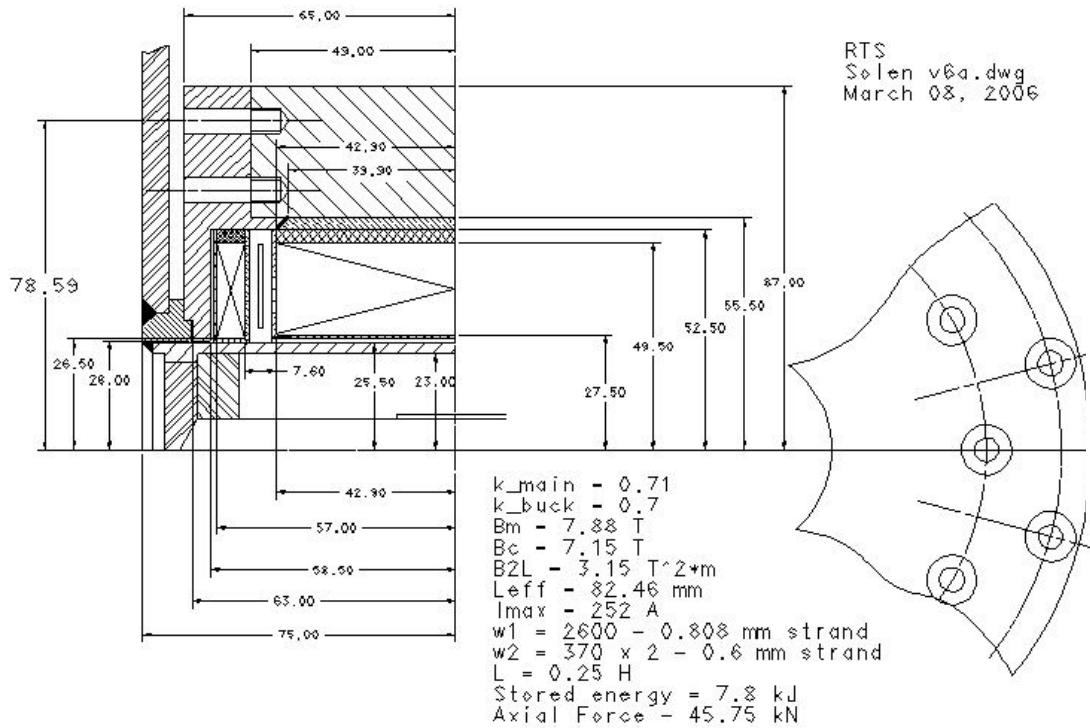
$T = 300\text{ K}$
 $I = 0\text{ A}$

$T = 4\text{ K}$
 $I = 0\text{ A}$

$T = 4\text{ K}$
 $I = 300\text{ A}$



Stress Management



Quench Protection Issues

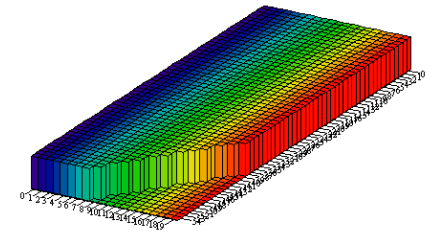
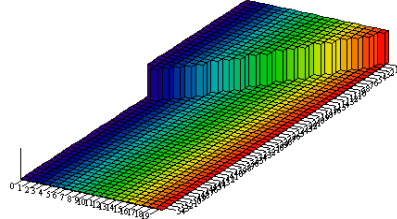
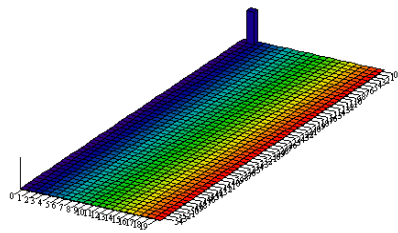
How quench propagates ? How long it takes ?

What can be the maximal temperature in the coil ?

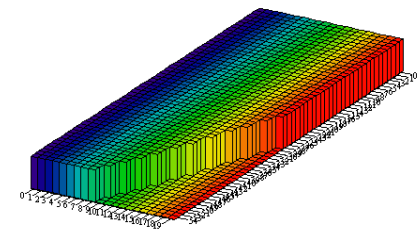
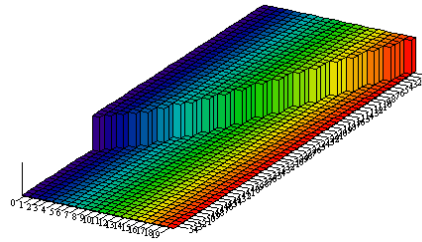
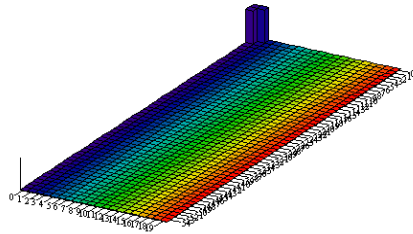
Main results of the study can be found in:

- | | |
|--|-----------|
| 1. Focusing Solenoid Quench Protection Studies.
Part I: Method Description and the First Iteration. | TD-06-003 |
| 2. Focusing Solenoid Quench Protection Studies.
Part II: Test Solenoid Quench Protection. | TD-06-004 |
| 3. Solenoid Quench Heater | TD-06-006 |
| 4. Review 12-02-2005 | |

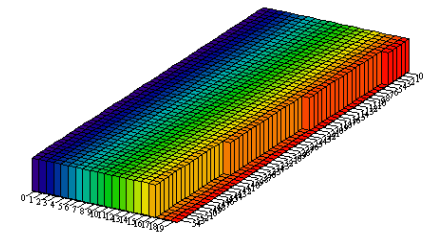
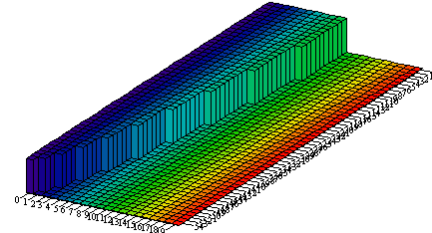
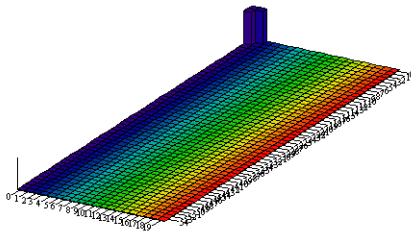
Quench Propagation



a) $I = 200$ A; $t = 3.5$ ms, 90 ms, 220 ms



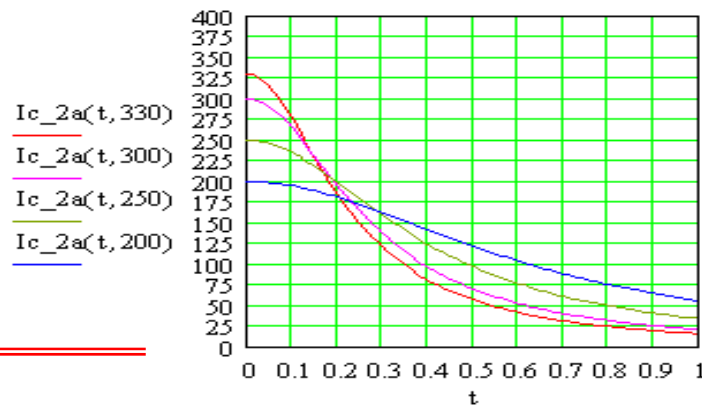
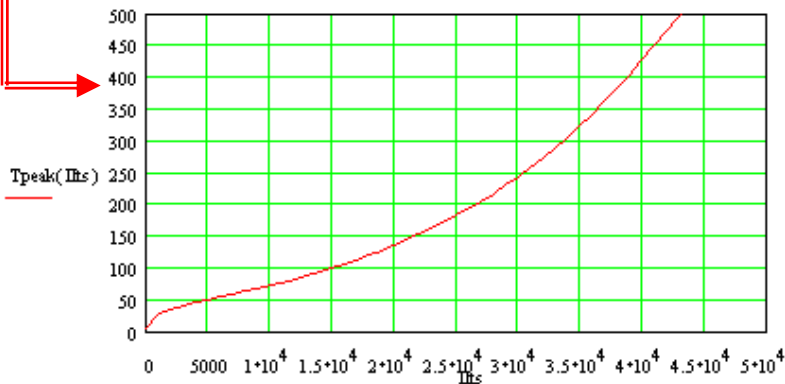
b) $I = 250$ A, $t = 2$ ms, 70 ms, 120 ms



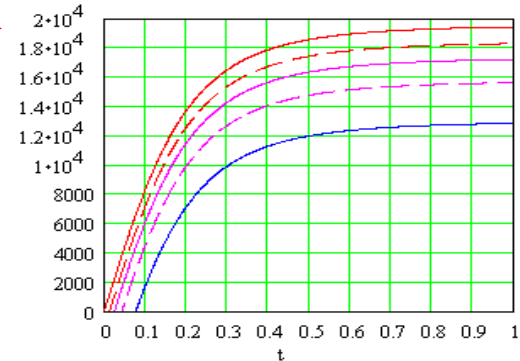
c) $I = 330$ A, $t = 0.3$ ms, 12.5 ms, 44 ms

Coil Heating

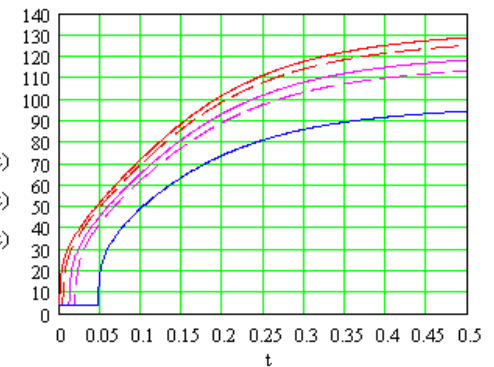
$$\int_0^t I^2(t) dt = A_{tot}^2 \int_{T_b}^T \frac{C_p(T)}{\rho(T, B)} dT$$



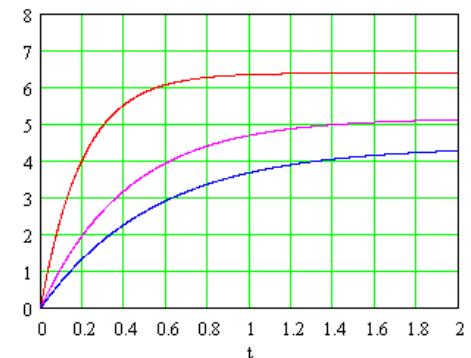
$IIT1(1, 1, 300, t)$
 $IIT1(25, 1, 300, t)$
 $IIT1(25, 10, 300, t)$
 $IIT1(55, 10, 300, t)$
 $IIT1(55, 20, 300, t)$



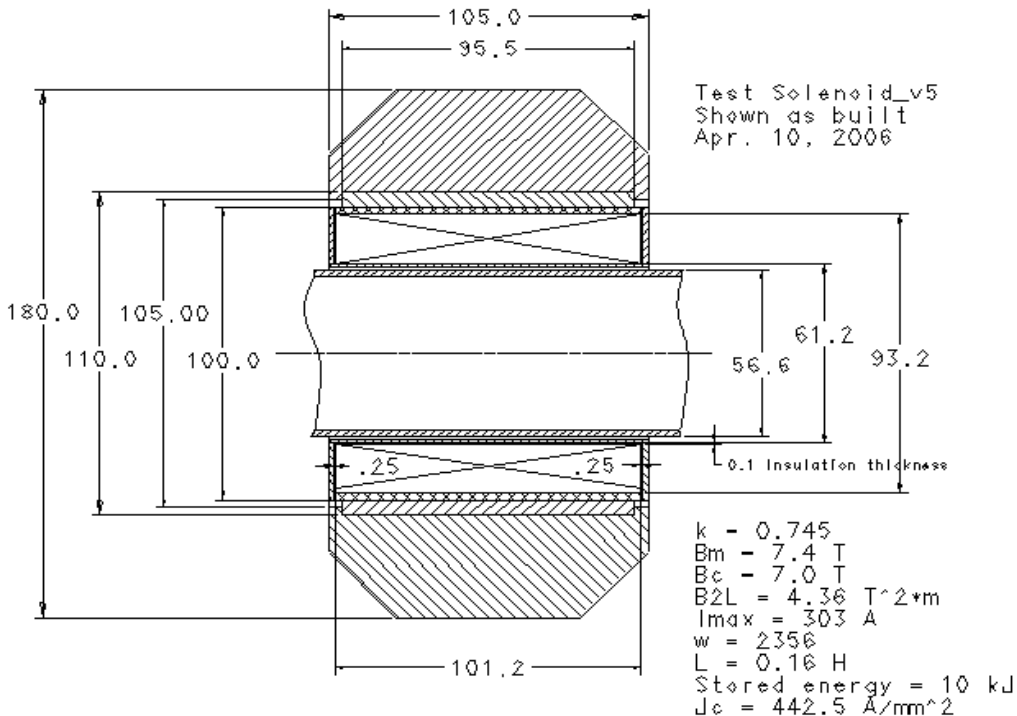
$T(1, 1, 330, t)$
 $T(25, 1, 330, t)$
 $T(25, 10, 330, t)$
 $T(55, 10, 330, t)$
 $T(55, 20, 330, t)$



$Rcoil(t, 330)$
 $Rcoil(t, 250)$
 $Rcoil(t, 200)$



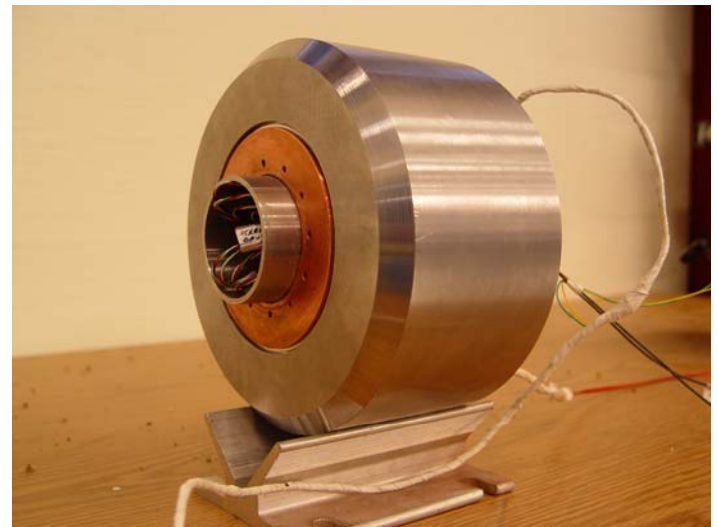
Test Solenoid Program



Expected Quench Current – 306.8 A

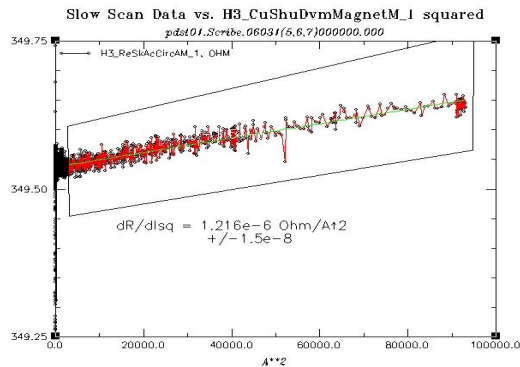
Central Field at quench current – 7.1 T

Maximal Field in the Coil – 7.5 T



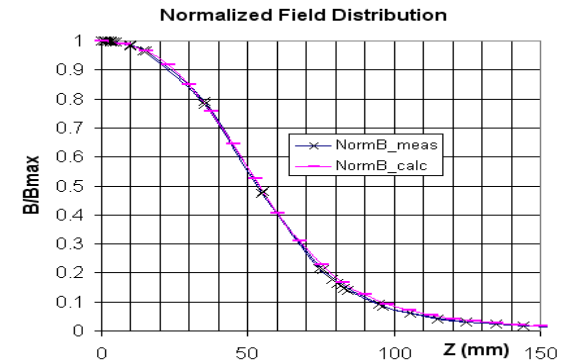
Main Test Results So Far

Stress history



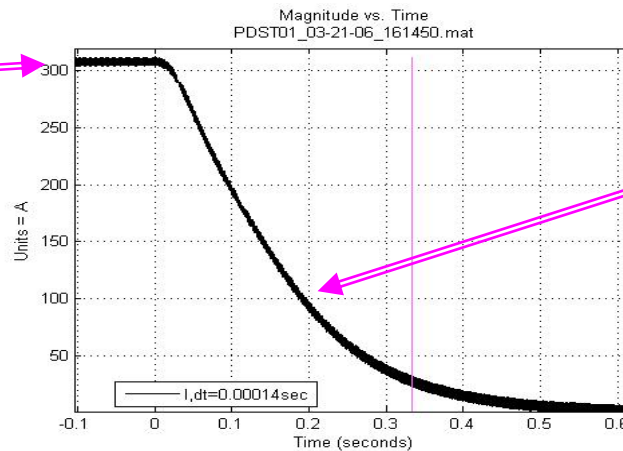
Measured and calculated field distribution

Layer-numbers	Quench-onset-at-308-A.(ms)
1-2	0
3-4	3
5-6	7
7-10	25
11-14	40
15-20	No records



Current shape

Quench current is within 1% from the prediction



Quench propagation rate is as expected



Tentative R&D Schedule

	2005				2006				2007			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Iterating on Requirements	■	■	■	■	■							
Strand R&D		■	■	■	■	■						
Magnetic Modeling		■	■	■	■	■	■	■				
Mechanical Model Program		■	■	■								
Stress Management Study		■	■	■	■	■						
Quench Protection Study			■	■								
Stand 3 modification		■	■	■	■	■						
Measurement system development		■	■	■	■	■	■	■				
Test Coil Program		■	■	■	■	■						
PDST-01				■	■							
PDST-02					■	■						
PDST-03						■	■					
Decision on Strand Choice						★						
CH Section Cold Mass Design					■	■	■					
CH Section Cold Mass Prototype							■	■				
CHCM Design Package							■	■				
Decision on the CHCM Fabrication								★				
CH Section Cryostat Development	■	■	■	■	■	■	■	■	■	■	■	■
SS-1 Section Cold Mass Design							■	■				
SS-1 Section Cold Mass Prototype								■	■			
Decision on the SSCM-1 Fabrication									★			
SS-2 Section Cold Mass Design								■	■			
SS-2 Section Cold Mass Prototype									■	■		
Decision on the SSCM-2 Fabrication										★		
Solenoid Acceptance Procedure							■	■				
Acceptance Test Infrastructure								■	■	■	■	
CH Section Solenoid Cryostat Design							■	■				
Test Cryostat Procurement for FS-CH								■	■			
Test FS-CH Assembly & Test									■	■		
Decision on the FS-CH Fabrication										★		

